

# **Flow and Regime Dependent Mesoscale Predictability**

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## **LONG-TERM GOALS**

The ultimate goals of the proposed work are to estimate the predictability of mesoscale features embedded within different synoptic-scale flow regimes and to identify key physical processes that control the limit of predictability at the mesoscale through explicit simulations of idealized moist baroclinic waves and case studies of high-impact weather events.

## **OBJECTIVES**

Major objectives of this research include:

- (1) Determine key dynamical differences in the flows that lead to different mesoscale error growth dynamics between two major extratropical cyclogenesis events;
- (2) Generalize results of flow-dependent mesoscale predictability concluded from real case studies through explicit simulations of idealized moist baroclinic waves;
- (3) Explore differences between warm-season and cold-season error-growth dynamics;
- (4) Synthesize flow-dependent mesoscale error growth dynamics with conceptual models.

Our working hypothesis, a multistage conceptual model, is that moist processes impose fundamental limits on mesoscale predictability but the error-growth dynamics is strongly dependent on the larger-scale background flow and its attendant dynamics.

## **APPROACH**

Since the beginning of the project a year ago, three graduate research assistants (Andrew Odins, Dan Hawblitzel and Jason Sippel) and a postdoctoral research associate (Dr. Naifang Bei) have been fully or partially trained/sponsored by this project. Odins completed and defended successfully his master's thesis in the fall of 2004 on the mesoscale predictability of an extreme warm-season south-central Texas flooding event of June-July 2003 (Odins 2004; Zhang et al. 2005). Hawblitzel completed and defended successfully his master's thesis on the impact of moist convection on the predictability of a long-lived mesoscale convective event of 10-13 June 2003 (Hawblitzel 2005; Hawblitzel et al. 2005). Sippel started his Ph.D. study in January and is working on the short-term predictability of tropical cyclones using ensemble forecasts, especially formed near the coastal areas of the United States.

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Dr. Bei has been working on several areas of the project including

- (1) mesoscale predictability of the Storm of the Century of March 1993 (“SOC”) and its comparison to another well-studied cold-season event, the ‘surprise’ snowstorm of January 2000;
- (2) mesoscale predictability of warm-season torrential rainfall events along the Meiyu fronts in China;
- (3) mesoscale predictability of idealized moist baroclinic waves with high-resolution simulations and diagnosis which contributes significantly to the synthesis of conceptual mesoscale error growth model.

The PI, Dr. Fuqing Zhang, has been actively working on and coordinating all aspects of the project. We have also collaborated closely with Drs. Zhe-Min Tan (Nanjing University), Craig Epifanio (Texas A&M), Chris Snyder (NCAR) and Rich Rotunno (NCAR) on idealized simulations and predictability of moist baroclinic waves as well as with Drs. Chris Davis (NCAR) and John Nielsen-Gammon (Texas A&M) on the warm-season predictability of high-impact events.

For the first objective in examining the mesoscale predictability of the “SOC” and its comparison to the “surprise” snowstorm, we performed experiments identical to those in Zhang et al. (2003). We also examine sensitivity for both cases by introducing perturbations at different stages of the cyclogenesis.

The MM5-based procedure developed in Tan et al. (2004) is used to create balanced initial conditions for simulating idealized moist baroclinic waves. This procedure includes using 3-dimensional potential vorticity (PV) inversion technique to invert the balanced finite amplitude baroclinic waves from specification of the background 3-D PV field. We further extended the low-resolution results from Tan et al. (2004) to convective-resolving simulations. We will be also testing error growth sensitivity to different flow configurations of moist baroclinic waves including sensitivity to the 2-D jet strength, Coriolis force, surface temperature gradient, and static stability.

To further explain the difference of error growth found between the two observed cases and to explore factors other than moist convection and background baroclinicity in limiting mesoscale predictability in a controlled environment, we will extend our idealized predictability study of Tan et al. (2003) through explicit simulations of moist baroclinic waves by

- (1) introducing surface/boundary layer inhomogeneities,
- (2) adding perturbations at difference phase of the cyclogenesis,
- (3) adding background barotropic shear to the initial baroclinic jet, and/or
- (4) constructing more realistic configurations with different initial baroclinic and static stabilities.

For the warm-season Texas flooding event of 2002, we will perform the high-resolution sensitivity experiments initialized at two different times per day. Little changes in the synoptic flows through the 8-day event allow us to examine/generalize the role of CAPE variation, diurnal cycle and cold pool dynamics in modulating and limiting short-range mesoscale predictability of such an extreme warm-season flooding event.

In all the performed/proposed sensitivity experiments, we examine both the intrinsic and practical aspects of mesoscale predictability in which realistic and/or small amplitude errors in both the forecast model and initial conditions are considered. Three forms of idealized initial perturbations as a function of initial spatial scales are tested:

- (1) a monochromatic small-scale wave as in Zhang et al. (2003);
- (2) “grid-point” random noises with energy equally projected to all scales as in Tan et al. (2004); and
- (3) large-scale random but balanced initial errors through inversion of the randomly-perturbed geostrophic streamfunction in the WRF/MM5 3Dvar system (Barker et al. 2003).

For quantitative evaluation of error evolution, we continue to use the diagnostics developed and implemented in our previous studies (Zhang et al. 2002, 2003; Tan et al. 2004) which include tracking difference energy growth between forecasts and performing spectral analysis of the difference energy.

## **WORK COMPLETED**

We have made significant progress in each of the four major objectives we proposed during the past year. We have nearly completed all the proposed model simulations and sensitivity experiments for both real-case studies and idealized moist baroclinic waves. We also extended our case studies to include the predictability of tropical cyclones, warm-season MCVs, and heavy precipitation along the meiyu front of East Asia.

We also develop advanced diagnostic tools including two-dimensional spectral decomposition and difference error energy budget analysis to quantify error growth and scale interactions more accurately. Both of these advanced diagnostic tools greatly enhanced our conceptual understanding of error growth characteristics under the influence of moist convection.

## **RESULTS**

There are two graduate theses fully sponsored by this project completely written and successfully defended during the past year (Odins 2004; Hawblitzel 2005). We also completed publication of Tan et al. (2004) which was partially sponsored by this project. Three other peer-reviewed journal papers (Zhang 2005; Zhang et al. 2005a; Nielsen-Gammon et al. 2005) partially/fully sponsored by this project have been accepted and in press for publications. Another manuscript of Hawblitzel et al. (2005) has been submitted for publication and completed two more manuscripts (Zhang et al. 2005b; Bei and Zhang 2005) are in internal review process to be submitted for publication. A brief summary of these publications/publications are listed below:

*(1) Mesoscale predictability of an extreme warm-season precipitation experiments (Zhang et al. 2005a; Nielsen-Gammon and Zhang et al. 2005; Odins 2004):*

A mesoscale model is used to investigate the mesoscale predictability of an extreme precipitation event over central Texas on 29 June 2002 that lasted through 7 July 2002. Both the intrinsic and practical aspects of warm-season predictability, especially quantitative precipitation forecasts up to 36 h, were explored through experiments with various grid resolutions, initial and boundary conditions, physics parameterization schemes, and the addition of small-scale, small-amplitude random initial errors. It is

found that the high-resolution convective-resolving simulations (with grid spacing down to 3.3km) do not produce the best simulation or forecast. It was also found that both the realistic initial condition uncertainty and model errors can result in large forecast errors for this warm-season flooding event. Thus, practically, there is room to gain higher forecast accuracy through improving the initial analysis with better data assimilation techniques or enhanced observations, and through improving the forecast model with better resolved or parameterized physical processes. However, even if a perfect forecast model is used, small-scale, small-amplitude initial errors, such as those in the form of undetectable random noise, can grow rapidly and subsequently contaminate the short-term deterministic mesoscale forecast within 36 h. This rapid error growth is caused by moist convection. The limited deterministic predictability of such a heavy precipitation event, both practically and intrinsically, illustrates the need for probabilistic forecasts at the mesoscales.

*(2) Mesoscale predictability of a warm-season torrential rainfall event along the Mei-yu front of China (Bei and Zhang 2005):*

The practical and intrinsic aspects of mesoscale predictability of a heavy rainfall event along the Mei-yu front of central China was studied through varying model resolutions, initial conditions and the addition of small-scale, small-amplitude random or balanced initial errors. In comparison to a recent study on an extreme warm-season flooding event over south-central Texas of the United States conduct, it is found that there are many similarities of practical predictability between these two events in both of which both the realistic initial condition uncertainties and model errors (which are both significantly large at present) can result in large forecast errors. However, there are significance differences in terms of error amplitude and growth rate between these two events. Error grows much faster in the Mei-yu event than that of the South-Central Texas flooding event likely due to a larger area of stronger CAPE in the former case. To further quantify the impacts of moist convection and other physical processes on mesoscale predictability, a budget analysis of the difference kinetic energy between the perturbed and unperturbed experiments has been conducted for the Mei-yu front case. Time evolution and vertical distribution of different source/sink terms in the energy budget equation of the Mei-yu event have been examined in comparison to the simulations of an idealized moist baroclinic waves. Considerable similarities and differences exist between these two different flow regimes which further demonstrates the flow-dependent nature of mesoscale predictability.

*(3) Mesoscale error dynamics and covariance structure of a winter cyclone (Zhang 2005):*

Several sets of short-range mesoscale ensemble forecasts generated with different types of initial perturbations are used in this study to investigate the dynamics and structure of mesoscale error covariance in an intensive extratropical cyclogenesis event that occurred on 24-25 January 2000. Consistent with past predictability studies of this event, it is demonstrated that the characteristics and structure of the error growth are determined by the underlying balanced dynamics and the attendant moist convection. The initially uncorrelated errors can grow from small-scale, largely unbalanced perturbations to large-scale, quasi-balanced structured disturbances within 12-24 h. Maximum error growth occurred in the vicinity of upper level and surface zones with the strongest PV gradient and over the area of active moist convection. The structure of mesoscale error covariance estimated from these short-term ensemble forecasts is subsequently flow-dependent and highly anisotropic, which is also ultimately determined by the underlying governing dynamics and associated error growth. Significant spatial- and cross-covariance (correlation) exists between different state variables with a horizontal distance as large as 1000 km and across all vertical layers. Qualitatively similar error

covariance structure is estimated from different ensemble forecasts initialized with different perturbations.

*(4) Probabilistic Evaluation of the Dynamics and Predictability of the Mesoscale Convective Vortex of 10-13 June 2003 (Hawblitzel 2005; Hawblitzel and Zhang et al. 2005):*

This study examines the dynamics and predictability of the mesoscale convective vortex (MCV) of 10-13 June 2003 through ensemble forecasting. The MCV of interest developed from a preexisting upper-level disturbance over the southwest United States on 10 June and matured as it traveled northeastward. This event is of particular interest given the anomalously strong and long-lived nature of the circulation. An ensemble of 20 forecasts using a two-way nested mesoscale model with horizontal grid increments of 30 and 10 km are employed to probabilistically evaluate the dynamics and predictability of the MCV. Ensemble mean and spread as well as correlations between different forecast variables at different forecast times are examined. It is shown that small-amplitude large-scale balanced initial perturbations may result in very large ensemble spread, ranging from a very strong MCV to no MCV at all. Despite similar synoptic-scale conditions, the ensemble MCV forecasts vary greatly depending on intensity and coverage of simulated convection, illustrating the critical role of convection in the development and evolution of this MCV. Correlation analyses reveal the importance of a preexisting disturbance to the eventual development of the MCV. It is also found that convection near the center of the MCV the following day may be an important factor in determining the eventual growth of a surface vortex, and that a stronger midlevel vortex is more conducive to convection, especially on the downshear side, consistent with findings of previous MCV studies.

*(5) Mesoscale predictability of moist baroclinic waves: Experiments with parameterized moist convection (Tan and Zhang et al. 2004):*

The present work represents a step on the path towards understanding how forecast errors grow. The vast majority of work on this topic is directed towards the modalities of error growth on the synoptic scale where effects of moisture might plausibly be neglected [see ZSR03 for a review]. Using a forecast model that is representative of those currently used for mesoscale numerical weather prediction (MM5), including the standard “physics”, we have examined how errors grow as a function of the moist instability within the context of a simple, but realistic, synoptic-scale development represented by the downstream development of a baroclinic wave. Our results indicate that without the effects of moisture, there is little error growth in the short term (0-36 h) difference between two simulations (starting from random noise), even though the basic jet used here produces a rapidly growing synoptic-scale disturbance. This result generalizes that of ZSR03 obtained from a single case study. There are also noticeable differences between the current idealized study and ZSR03. Direct comparisons show that the 36-h amplification of errors in the present (CNTL) simulations is about half of that found in ZSR03 at the same resolution. The reasons for these differences are not certain at this time, but differences in the amplitude of the parent baroclinic wave, the details of its development, or lack of a large area of convective instability (which is associated with the warm Gulf Stream in ZSR03), are possible contributors.

*(6) Mesoscale predictability of moist baroclinic waves: Cloud-resolving experiments and multistage error growth dynamics (Zhang et al. 2005b):*

A recent study by the authors (Tan et al. 2004) examined the predictability of an idealized baroclinic wave amplifying in a conditionally unstable atmosphere through numerical simulations with

parameterized moist convection. It was demonstrated that with the effect of moisture included, the error starting from small random noise is characterized by upscale growth in the short term (0-36 h) forecast of a rapidly growing synoptic-scale disturbance. The current study seeks to further explore the mesoscale error growth dynamics in the idealized moist baroclinic waves through cloud-resolving experiments with model grid increments down to 3.3km. A multistage error growth conceptual model is proposed. In the initial stage, the errors first grow from small-scale convective instability and then quickly saturate at the convective scales on time scales of  $O(1\ h)$ . The amplitude of saturation errors may be a function of CAPE and its areal coverage determined by large-scale flows. In the transitional stage, the errors transform from convective-scale unbalanced motions to larger-scale balanced motions through geostrophic adjustment. Part of the errors due to difference in latent heating from convection may be retained in the balance fields while the others are radiating away in the form of gravity waves. In the final stage, the balanced components of the errors project onto the larger-scale flow and grow with the background baroclinic instability. Though an examination of the difference error energy budget, similar to the turbulence kinetic energy budget analysis, it is found that buoyancy production due mostly to moist convection is comparable to shear production due to nonlinear advection. Not only does turning off latent heating dramatically decrease buoyancy production, but it also reduces shear production (nonlinear advection) to less than 20% of its original amplitude. These new findings further demonstrate of the impacts of moist convection and diabatic heating on the limit of mesoscale predictability.

## **IMPACT/APPLICATIONS**

Understanding of the limit of mesoscale predictability and the associated error growth dynamics is essential for setting up expectations and priorities for advancing deterministic mesoscale forecasting and for providing guidance on the design, implementation and application of short-range ensemble prediction systems. Understanding the nature of mesoscale predictability is also crucial to the design of the efficient data assimilation systems for the meso- and regional scales.

## **RELATED PROJECTS**

*Collaborative Research: Ensemble-based State Estimation for Weather Research and Forecast Model. National Science Foundation (NSF); 09/01/02-08/31/06; \$295,000; (Principal Investigator).*

The NSF sponsored project closely related to this project because mesoscale predictability and data assimilation are two integral parts of state estimation. Data assimilation provides better initial condition to assess predictability while predictability points to the ultimate benefits and limitations of data assimilation.

*Dynamics and Impacts of Mesoscale Gravity Waves. National Science Foundation (NSF); 09/15/02-08/31/06; \$224,834; (Principal Investigator).*

The NSF sponsored project closely related to this project because gravity wave dynamics and geostrophic adjustment play an important role in understanding the upscale growth of error energy from moist convection which limits to limit of mesoscale predictability.

## REFERENCES

- Barker, D., W. Huang, Y.-R. Guo and A. Bourgeois, 2003: A three-dimensional variational (3DVAR) data assimilation system for use with MM5. *NCAR Technical Note*, **NCAR/TN-453+STR**, 68pp.
- Zhang, F., C. Snyder, and R. Rotunno, 2002: Mesoscale predictability of the 'surprise' snowstorm of 24-25 January 2000. *Mon. Wea. Rev.*, **130**, 1617-1632.
- Zhang, F., C. Snyder, and R. Rotunno, 2003: Effects of Moist Convection on Mesoscale predictability. *J. Atmos. Sci.*, **60**, 1173-1185.

## PUBLICATIONS

1. Tan Z., **F. Zhang**, R. Rotunno, and C. Snyder 2004: Mesoscale predictability of moist baroclinic waves: Experiments with parameterized moist convection. *Journal of the Atmospheric Sciences*, **61**, 1794-1804 [published, referred].
2. **Zhang, F.**, A. Odins, and J. W. Nielsen-Gammon, 2005a: Mesoscale predictability of an extreme warm-season rainfall event. *Weather and Forecasting* [referred, in press].
3. Nielsen-Gammon, J., **F. Zhang**, and A. Odins, and B. Myoung, 2005: Extreme rainfall events in Texas: Patterns and predictability. *Physical Geography* [referred, in press].
4. **Zhang, F.**, 2005: Dynamics and structure of mesoscale error covariance of a winter cyclone estimated through short-range ensemble forecasts. *Monthly Weather Review* [referred, in press].
5. Hawblitzel, D., , Z. Meng, and C. A. Davis, 2005: Probabilistic evaluation of the dynamics and predictability of mesoscale convective vortex event of 10-13 June 2003. *Weather and Forecasting* [in peer review].
6. **Zhang, F.**, N. Bei, R. Rotunno, C. Snyder and C. C. Epifanio, 2005b: Mesoscale predictability of moist baroclinic waves: Cloud-resolving experiments and multistage error growth dynamics. *Journal of the Atmospheric Sciences* [in internal review].
7. Bei, N. and **F. Zhang**, 2005: Mesoscale predictability of the torrential rainfall along the Mei-yu front of China. *Advances in Atmospheric Sciences* [in internal review].
8. Hawblitzel, D., 2005: "Observations, dynamics and predictability of a mesoscale convective vortex event of 10-13 June 2003". *Master thesis*, Texas A&M University, 206pp [published].
9. Odins, A., 2004: "Mesoscale predictability of an extreme warm season precipitation event". *Master thesis*, Texas A&M University, 108pp [published].
10. Hawblitzel D., **F. Zhang**, Z. Meng, and C. A. Davis, 2004: Dynamics and predictability of MCVs estimated through high-resolution deterministic and probabilistic (ensemble) forecasts. The 22<sup>nd</sup> AMS Conference on Severe and Local Storms, October 2004, Hyannis, Massachusetts [conference abstract].

11. **Zhang, F.**, C. Snyder and R. Rotunno, 2004: Flow and regime dependent mesoscale predictability. *Symposium on 50th Anniversary of Operational Numerical Weather Prediction*. June 2004, College Park, Maryland [conference abstract].
12. Nielsen-Gammon, J., **F. Zhang**, and A. Odins, and B. Myoung, 2005: Extreme rainfall events in Texas: Patterns and predictability. *AMS Forum: Living with a Limited Water Supply*, January 2005, San Diego, California [conference abstract].
13. Snyder C., R. Rotunno **Zhang, F.**, and R. Moss, 2005: Another look at predictability in flows with many scales. *The Ed Lorenz Symposium*, January 2005, San Diego, California [conference abstract].
14. **Zhang, F.**, N. Bei, C. Snyder and R. Rotunno, 2005: Flow and regime dependent mesoscale predictability. *The Ed Lorenz Symposium*, January 2005, San Diego, California [conference abstract].
15. **Zhang, F.**, N. Bei, R. Rotunno, C. Snyder and C. C. Epifanio, 2005: Mesoscale predictability of moist baroclinic waves: Cloud-resolving experiments and multistage error growth dynamics. *The 21<sup>st</sup> AMS Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, D. C., August 2005 [conference abstract].
16. Hawblitzel, D., and **F. Zhang**, 2005: Probabilistic evaluation of the MCV dynamics and predictability. *The 21<sup>st</sup> AMS Conference on Weather Analysis and Forecasting/17th Conference on Numerical Weather Prediction*, Washington, D. C., August 2005 [conference abstract].